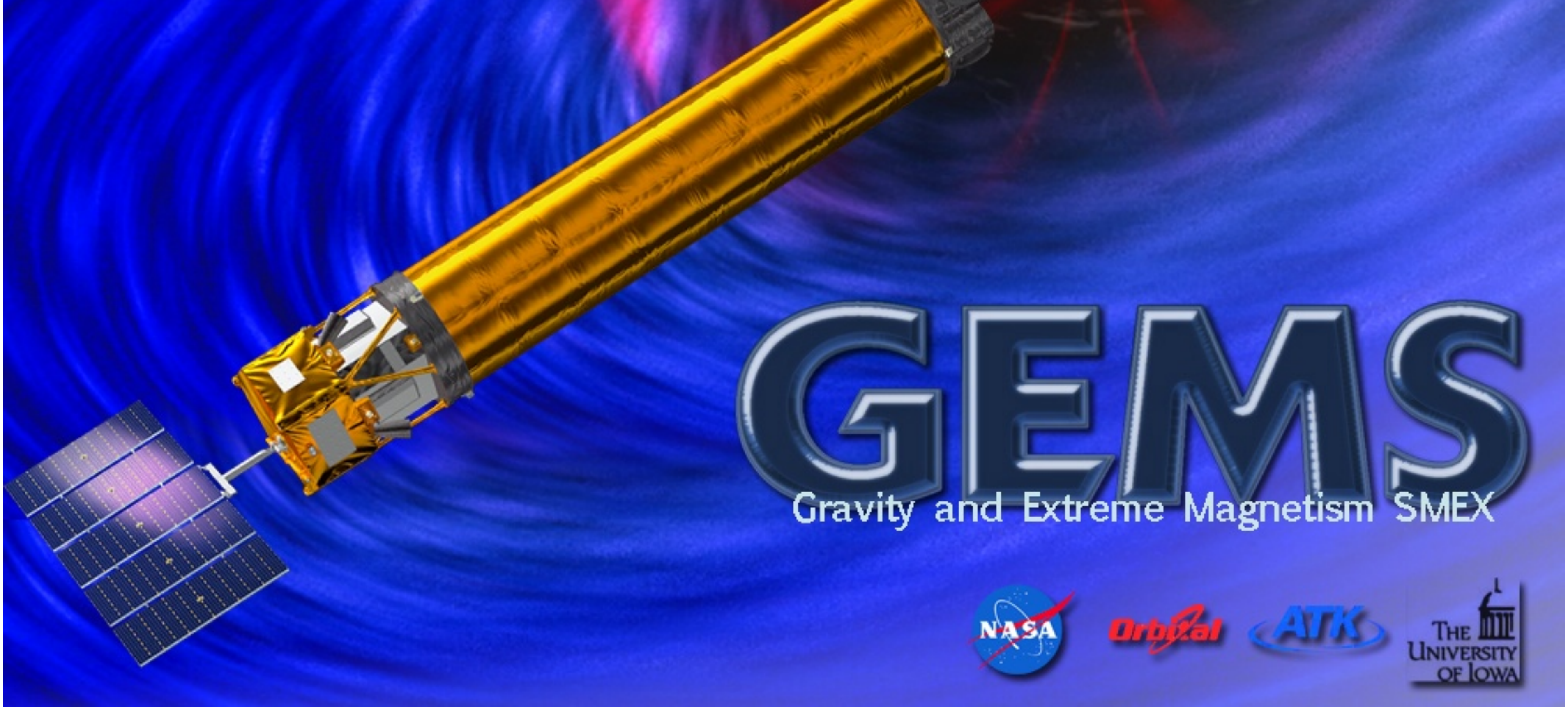
Tim Kallman for Jean Swank and the GEMS Team
Goddard Space Flight Center

IXO Meeting March 15 2011

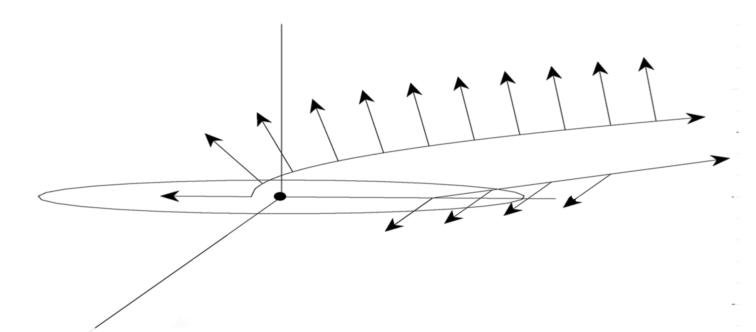


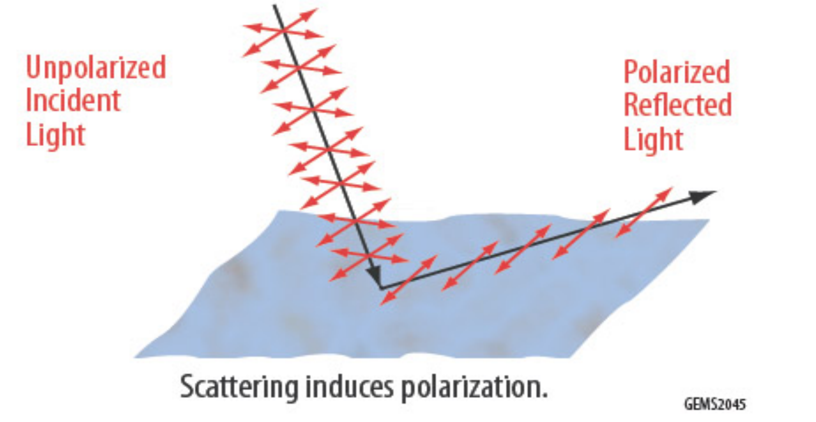
Outline

- GEMS Science Objectives
  - Why polarimetry?
  - Source classes: black holes, neutron stars, supernova remnants
- GEMS Overview
  - X-Ray Polarimetry Instrument
  - Bragg Reflection Polarimeter - Student Experiment
  - Mission Design
- Polarimeter Design and Performance
- Conclusions

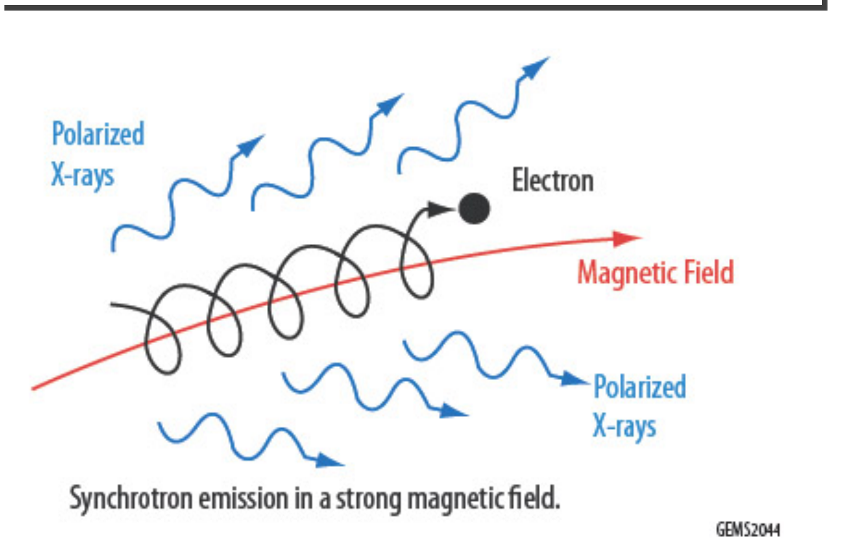
Polarimetry probes key physics of photon emission and propagation

- Polarization measurements allow us to study:
  - ✓ Scattering
  - ✓ Magnetic fields
  - ✓ Strong gravity





Scattering induces polarization.



Synchrotron emission in a strong magnetic field.

GEMS will use these processes to probe black holes, neutron stars and supernova remnants

X-ray polarimetry history: detection of the Crab

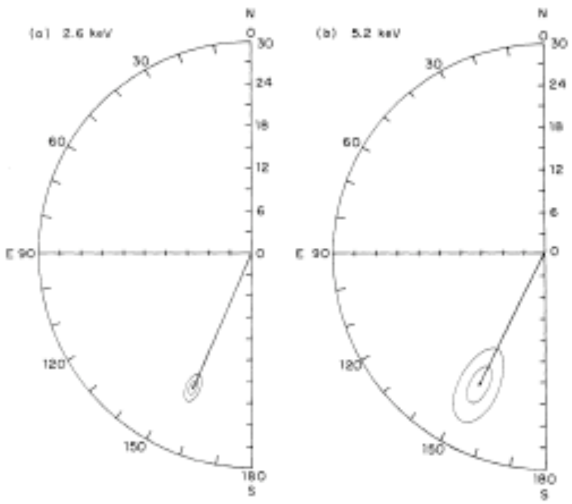


FIG. 3.—The polarization vectors for the Crab Nebula at (*a*) 2.6 keV and (*b*) 5.2 keV. Surrounding the vectors in order of increasing size are the 67% and 99% confidence contours. The radial scale is the polarization in percent.

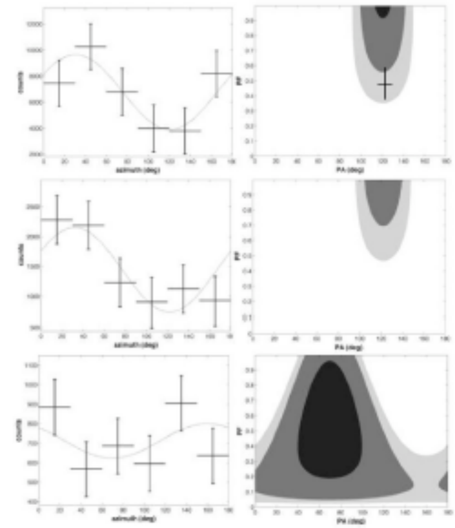


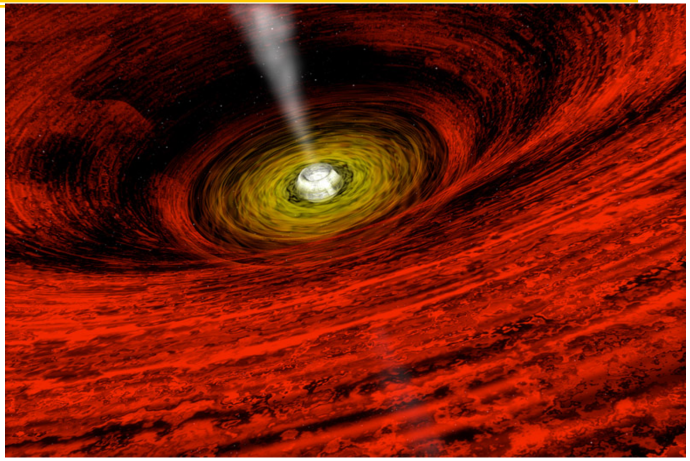
FIG. 2.—Azimuthal profile, modulation angle, PA, and fraction, PF = a_0/a_{100}, measured for the Crab data between 200 and 800 keV, in the off-pulse (*top*), off-pulse and bridge (*middle*), and two-peak (*bottom*) phase intervals. The error bars for the profile are at 1 σ. The 68%, 95%, and 99% confidence regions are shaded from dark to light gray. The SPI result (Dean et al. 2008) is indicated in the top figure by a cross.

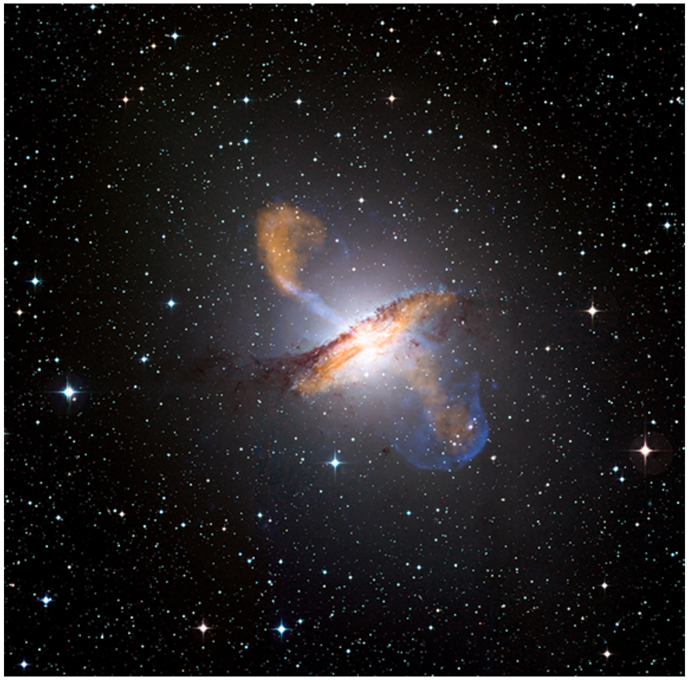
- **To measure nebular polarization, need to look a phases when pulsar is "off"**
- X-rays from nebula 19.2%±1.0% polarized at 156.4°±1.4° at 2.6 keV; 19.5%±2.8% polarized at 152.6°±4.0° at 5.2 keV (Weisskopf et al. 1978)
- γ-rays: Off pulse and bridge emission polarized at 122.0°±7.7° (Forot et al. 2008)
  - Consistent with 124°±0.1° projected pulsar rotation angle
  - PF>72% (off pulse) >88% (off pulse plus bridge)
  - Consistent with 77% polarized signal along pulsar rotation axis, maximum
- IBIS measurement probably from particles in equatorial wind near the termination shock.

  Electrons have energy as high as 250-500 TeV, lifetime of 0.85-0.43 year, and do not travel more than 0.09 pc.
- X-rays sample larger region (thus lower fraction); less order (thus different angle)

X-ray Polarimetry provides a new way to study black holes

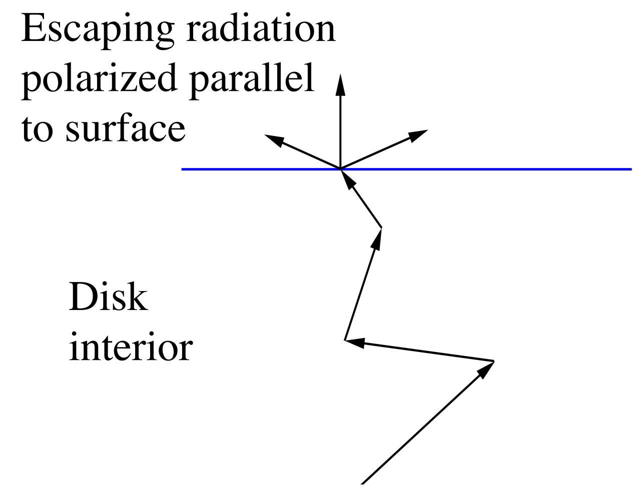
- X-rays are the best electromagnetic probe of conditions close to the event horizon
- This allows study of the structure of the accretion flow
- And of the black hole effects on spacetime
- Current models for spectra and timing make predictions of the polarization behavior, and we can test them
- Polarization also provides a complementary way to probe black hole spin

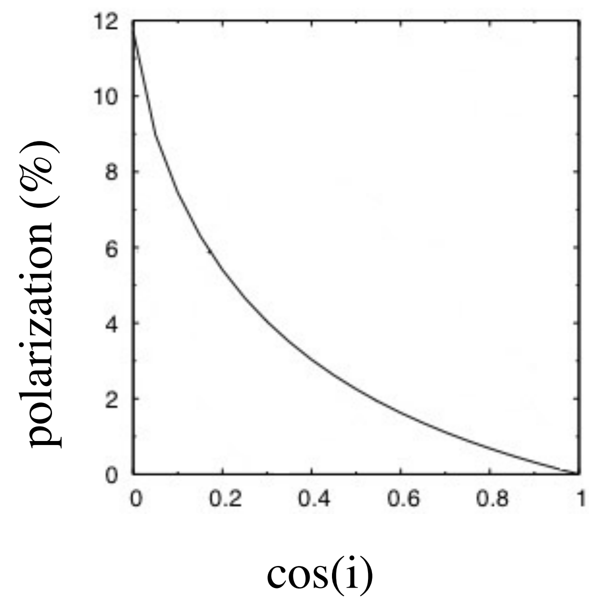




X-ray emission from soft state black holes is from disk accretion

- In an optically thick accretion disk, the atmosphere is dominated by Compton scattering
- Compton scattered radiation can be 100% polarized perpendicular to the scattering plane for a single 90° scattering
- In an atmosphere there are a range of scattering angles
- The polarized fraction is 0-12%, depending on inclination (Chandrasekhar 1960)
- The polarization direction is parallel to the disk surface





Propagation near a black hole reveals its gravity

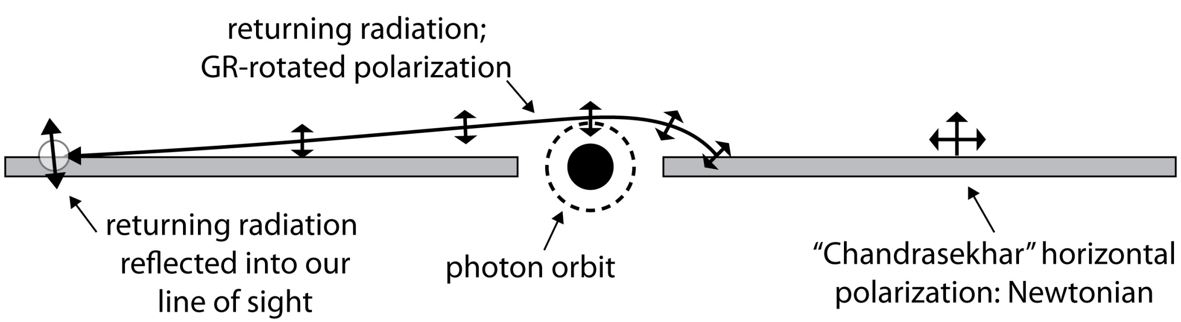
Propagation to the observer is affected by:

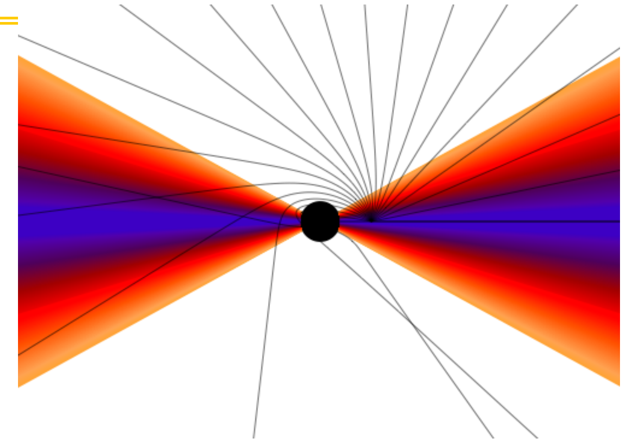
- Special relativistic effects: Doppler shift, aberration, beaming

- General relativistic effects: gravitational redshift, light-bending

Plus, the disk illuminates itself via gravitational effects

This returning radiation, which scatters 90^{o} into our line of sight, has a significant effect on polarization





(Schnittman)

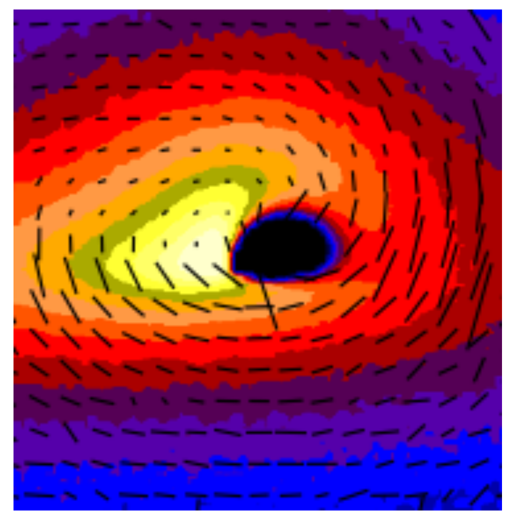
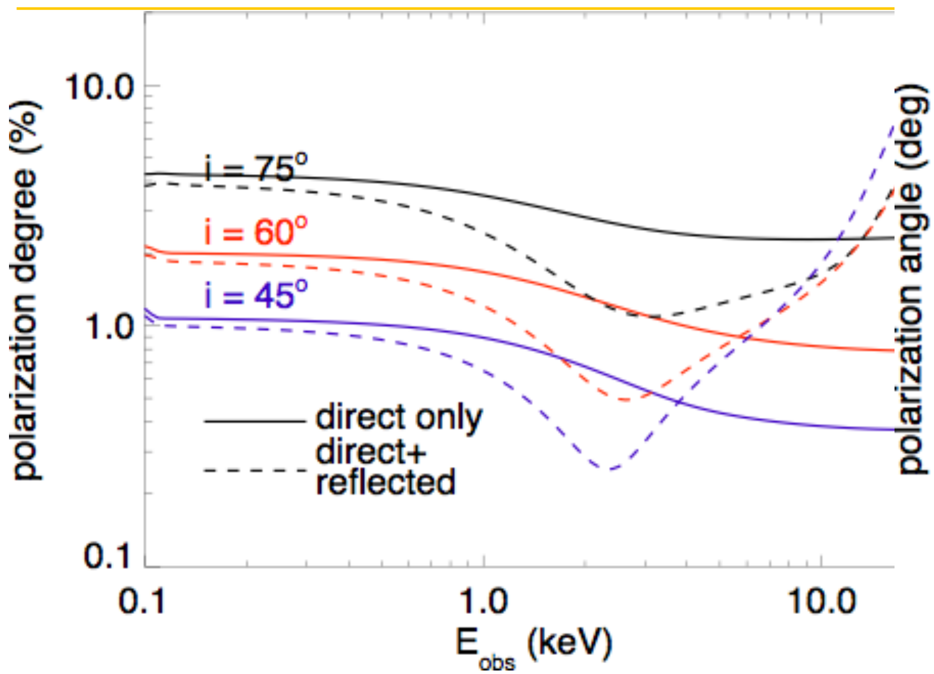
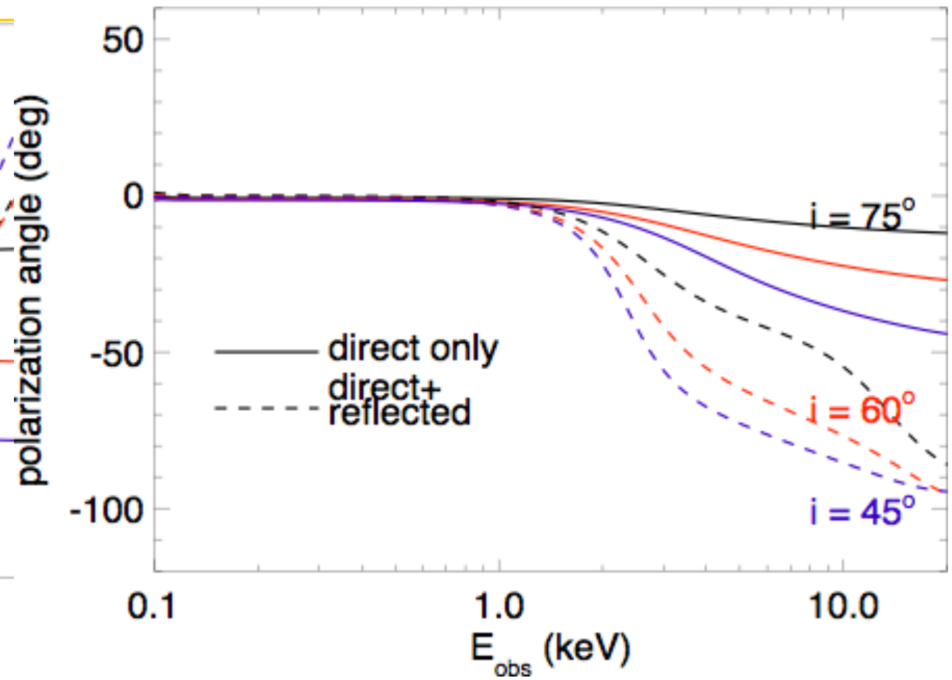


Image of disk showing intensity as color, polarization vectors $a/m=0.998$ $i=70^{o}$

Two regimes in black hole polarization behavior -



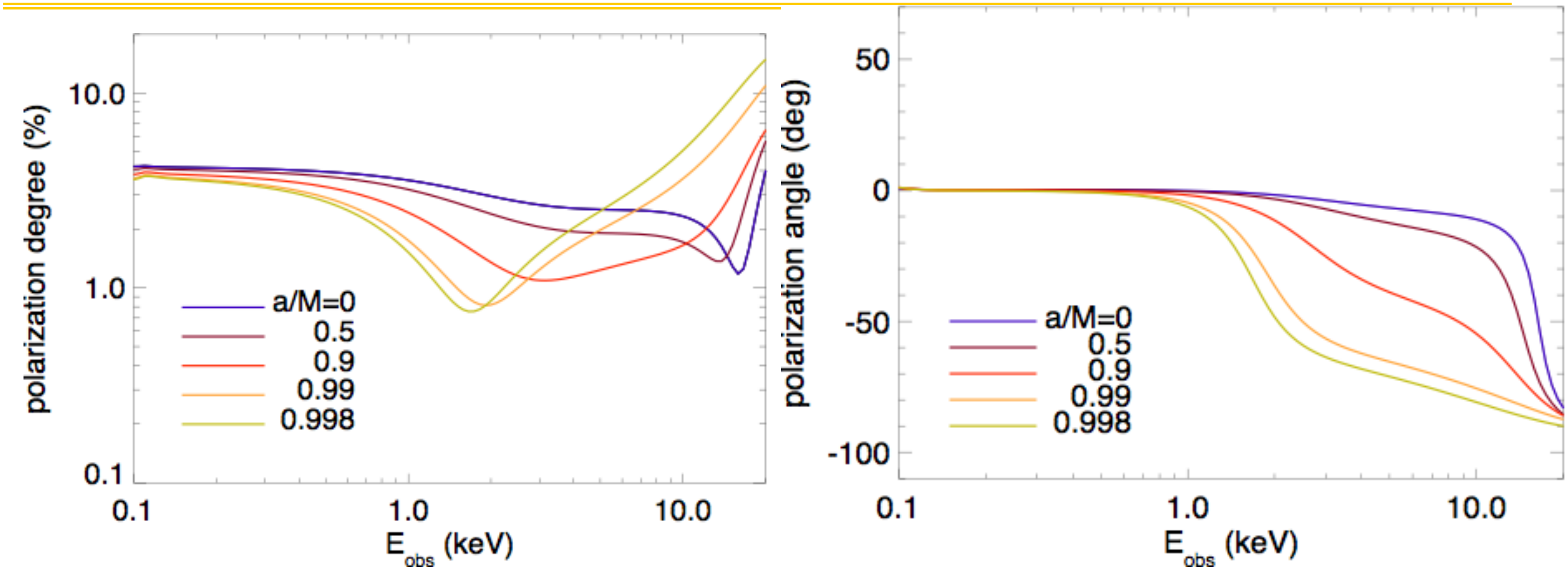


(Schnittman and Krolik 2009)

- At lower X-ray energies, photons are emitted far from the black hole
- Relativistic effects are weak
- Position angle is parallel to disk plane and is a function of inclination, as predicted by Chandrasekhar

- At higher energies, relativistic effects become important
- polarization direction becomes perpendicular to disk and fractional polarization increases

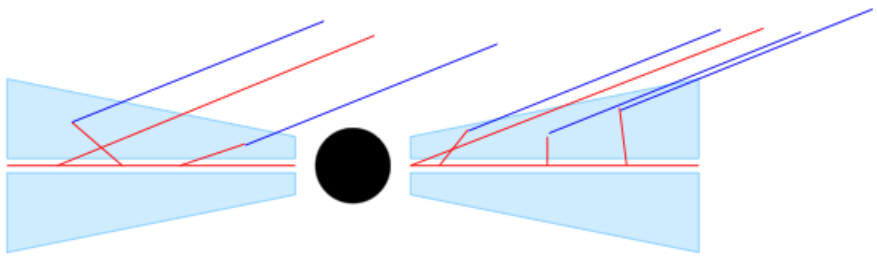
Strength of return radiation is sensitive to spin

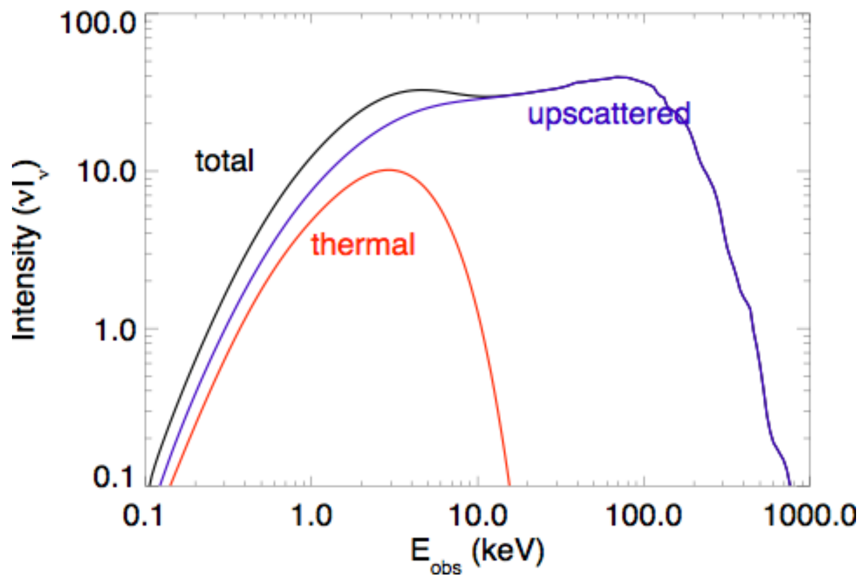


(Schnittman and Krolik 2009a)

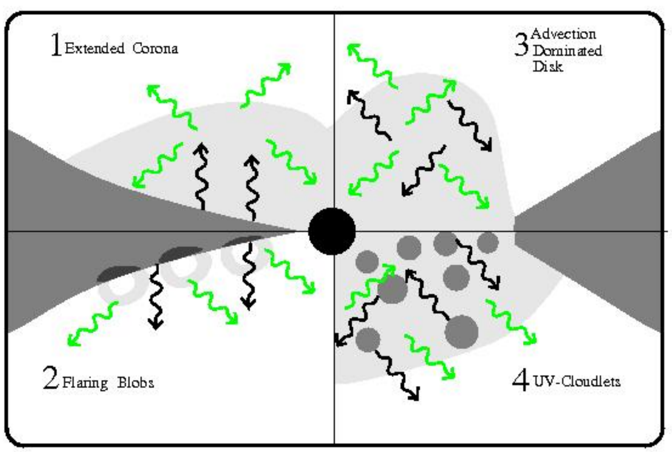
- Strength of return radiation depends on spin
- Therefore, transition energy between the direct and return-dominated regimes, and strength of high energy polarization, depend on spin

Black holes in the hard state: effect of a hot corona -



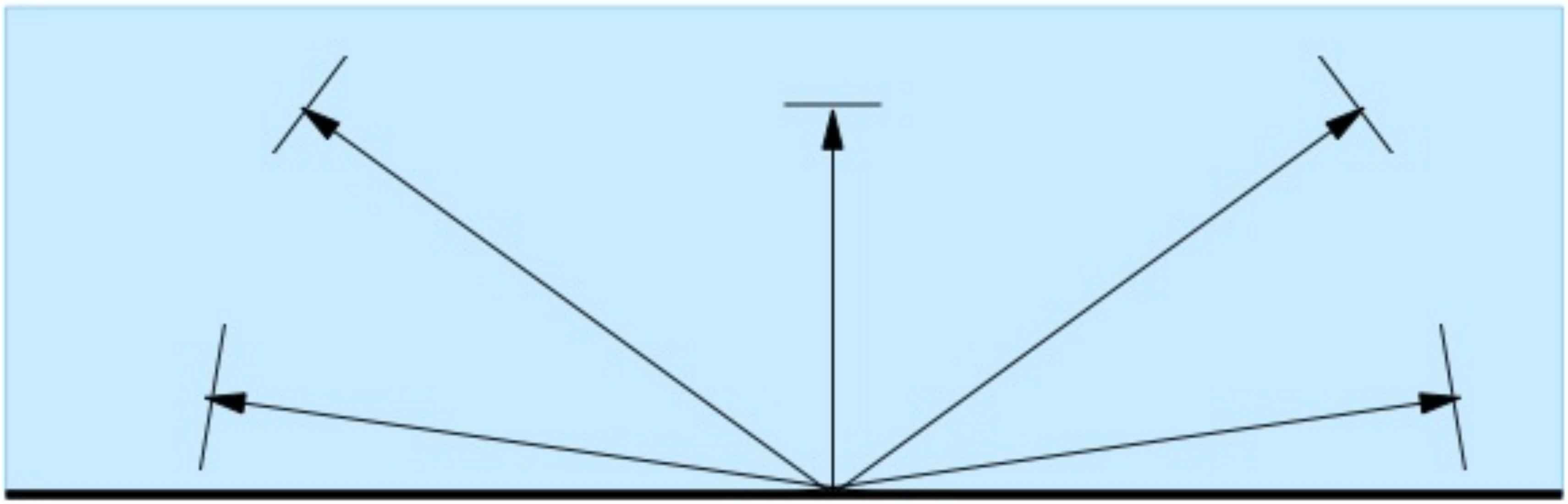


- Observed spectra in black hole 'hard state' are likely associated with Compton up-scattering of thermal photons by a hot ($\sim 10^9$K) corona
- This corona likely encloses some or all of the thermal disk
- Details of the corona conditions (extent, temperature, location) have not been well constrained by spectra or temporal signatures
- Polarization provides a means to do this…



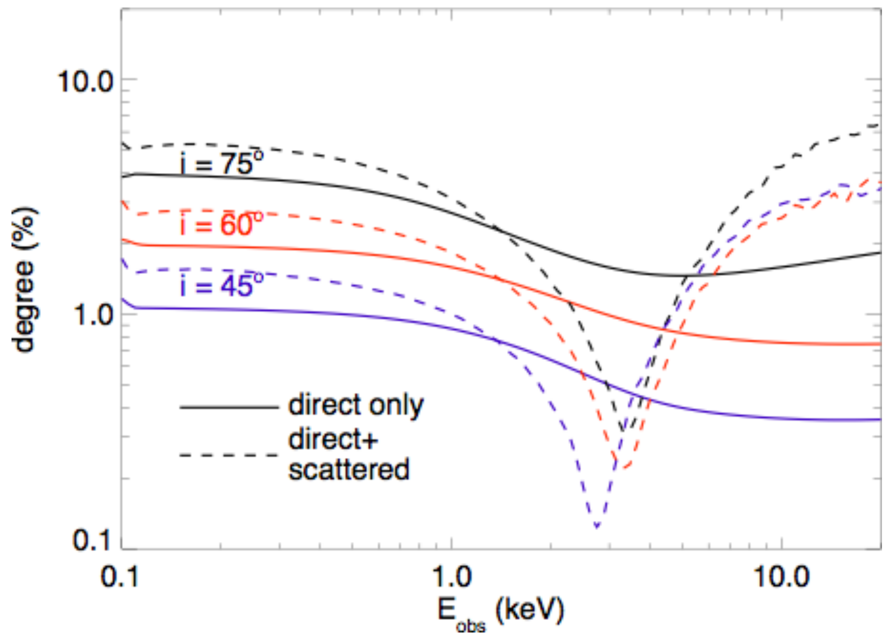
(Haardt 1996)

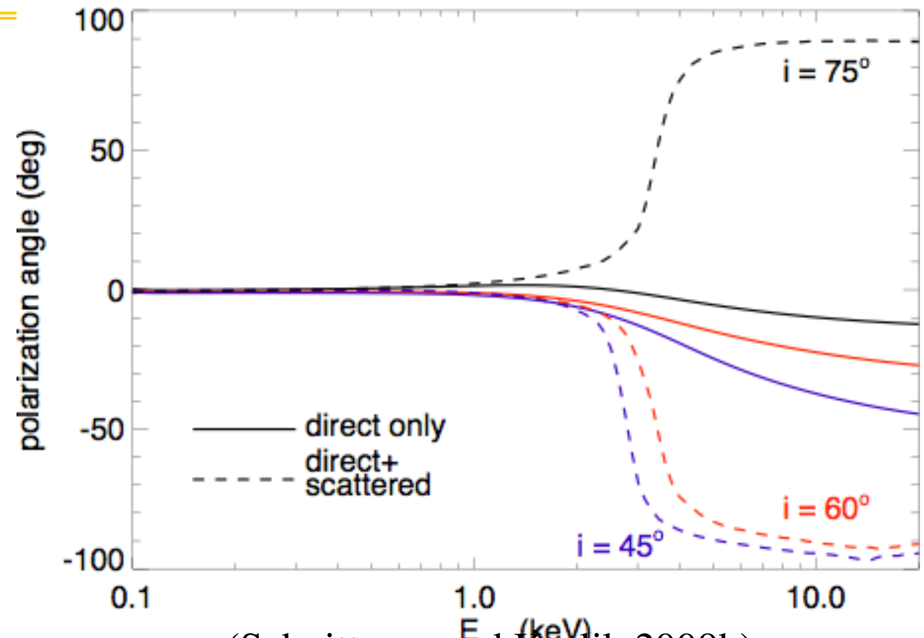
Scattering through optically thin corona produces net polarization perpendicular to the disk



- In electron scattering the polarization of observed photons is always perpendicular to the scattering plane
- If the corona is flattened there is a higher probability of scattering for photons parallel to the disk
- Thus the net polarization produced by scattering in the corona will be predominantly perpendicular to the disk

Corona scattering preferentially changes polarization of high energy photons





(Schnittman and Krolik 2009b)

- Figures show polarization fraction and angle vs energy for various choices of inclination angle and for the direct photons and those scattered in the corona

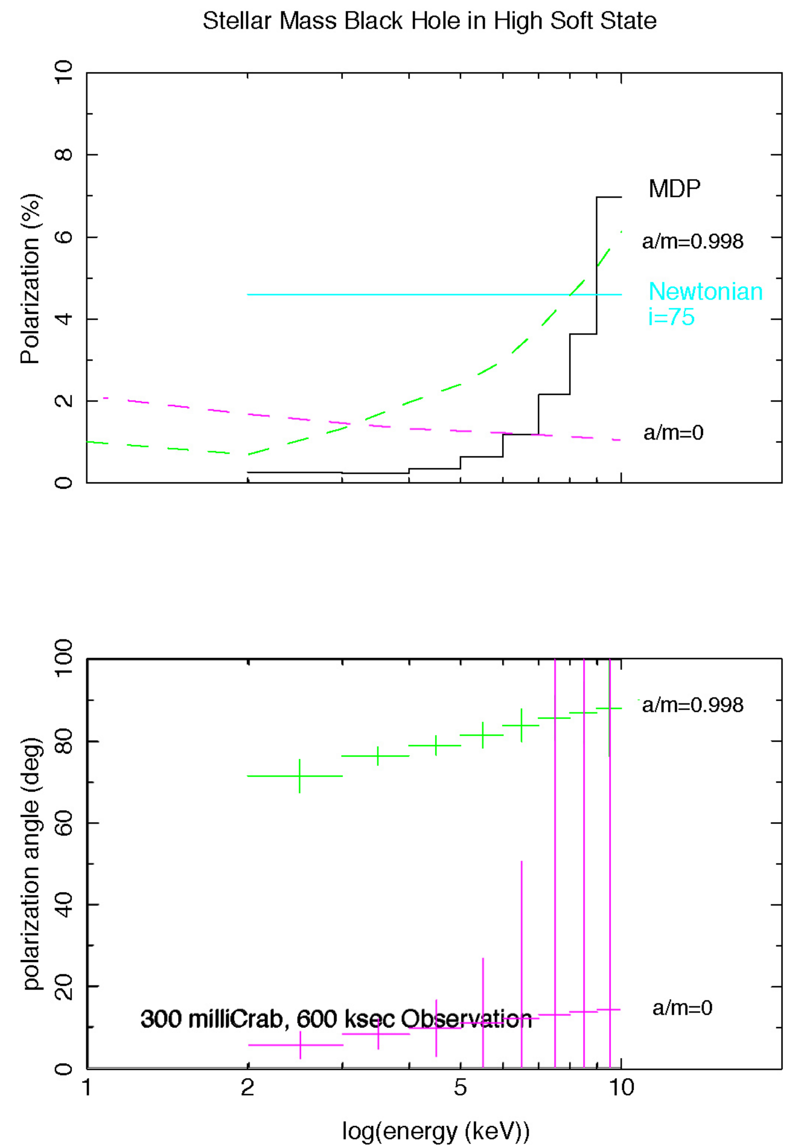
- Corona scattering selects vertically polarized photons, and so rotates net polarization direction by 90°

- Also increases the polarization fraction at high energies

- High energy polarization and transition energy are sensitive to the corona temperature and optical depth

GEMS observations can constrain black hole spin

- A GEMS observation of a stellar mass black hole in the thermal state can measure expected dependences on angular momentum
- Short observations (30 ksec) will be capable of detecting 1% polarization in 2-4 keV and 4-8 keV bands
- In the case of hard state black holes, gems will be able to test for the combined effects of spin and coronal geometry



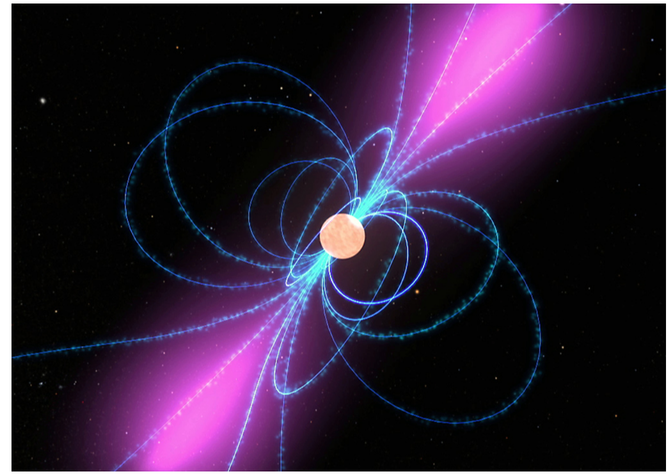
X-ray polarization from pulsars provides insight into strong magnetic fields, gravity, and QED

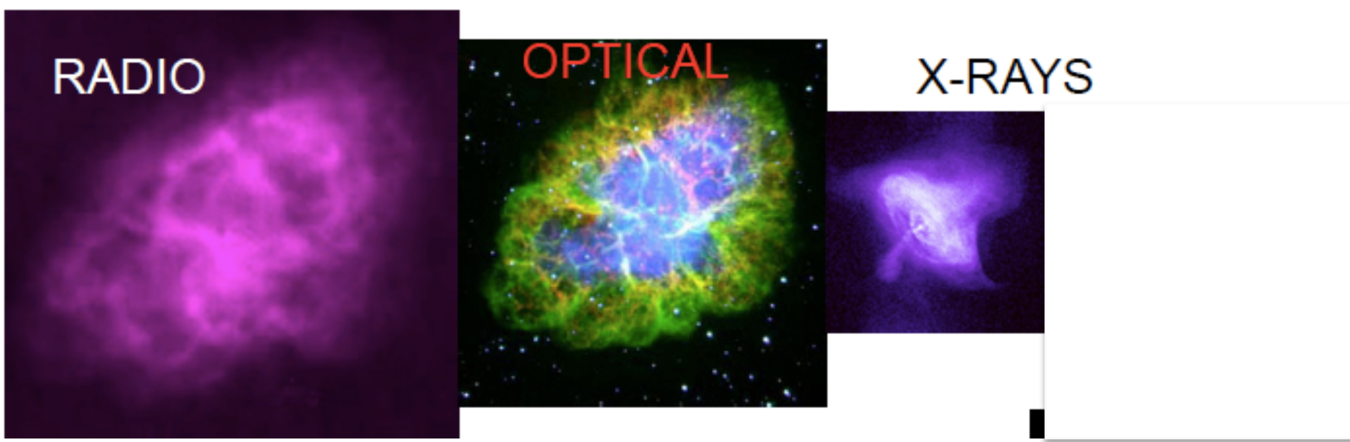
Electron scattering in strong magnetic fields is highly polarizing

This provides a way to learn about geometry of field and X-ray emitting region

Pulse phase observations provide changing view of neutron star

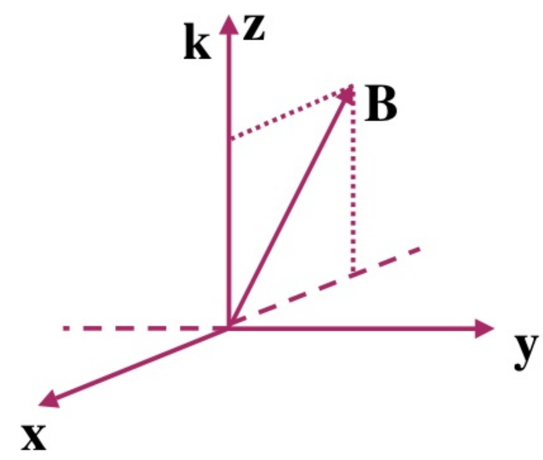
Propagation of polarized light provides further information: strong gravity and strong field effects





In the strongly magnetized plasma of neutron stars, scattering is affected by the field direction-

For energies below the cyclotron frequency ($\omega << \omega_{ce} = 11.6 B_1$ keV), photons divide into two propagation modes:



1) O-mode (parallel mode):

E nearly in the **k-B** plane

2) X-mode (perpendicular mode)

E nearly perpendicular to the **k-B** plane

The two modes have very different opacities

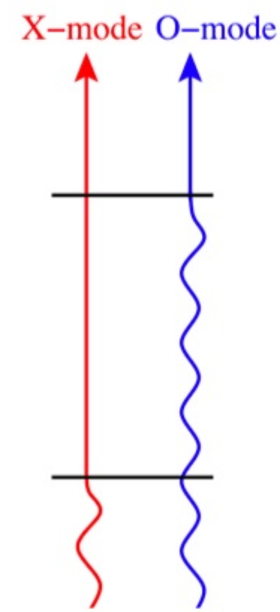
$\kappa_{\text{O-mode}} \sim \kappa_{B=0}$

$\kappa_{\text{X-mode}} \sim \kappa_{B=0} (\omega/\omega_{es})^2$

--> In a magnetized atmosphere, such as on a neutron star, the photosphere for X-mode is much deeper than the for O-mode

--> X-mode is the main carrier of X-ray flux

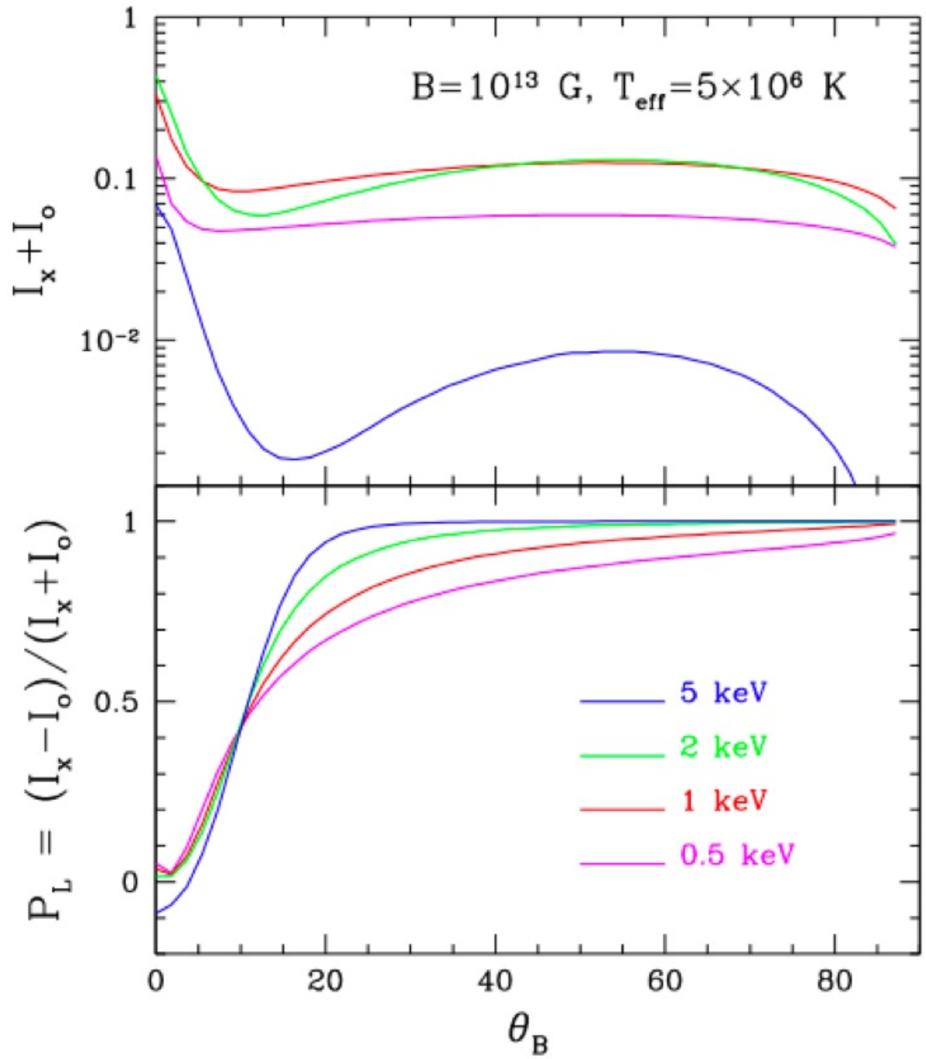
*--> X-rays are strongly polarized in the direction perpendicular to the **k-B** plane*



(Lai, Vanadelsberg, Heyl 2009)

Putting a polarimeter on the neutron star surface -

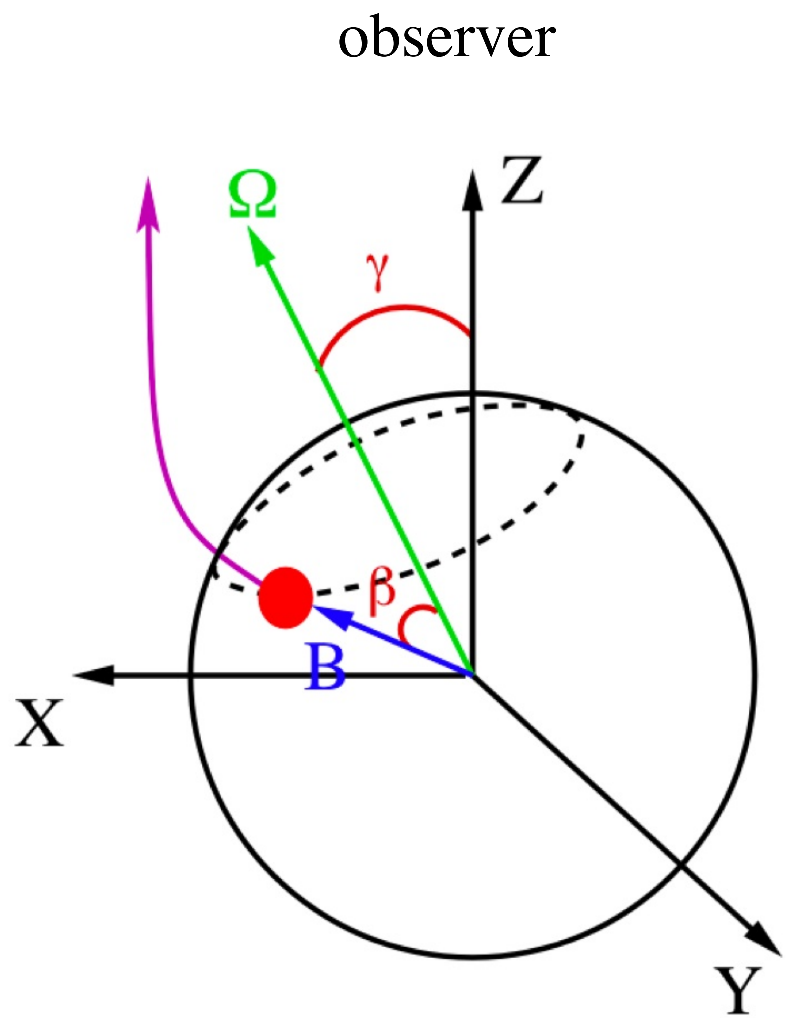
- At the neutron star surface, X-rays will be strongly polarized for all viewing angles >10° from **B**
- Polarization direction indicates field orientation



(Lai, Vanadelsberg, Heyl 2009)

After the photon leaves the surface, it is subject to..

- GR light bending
- Mixing with photons from elsewhere on the surface
- These effects will tend to dilute the net polarization
- QED effects, ‘vacuum polarization’, can effectively freeze the polarization to the field direction
- This counteracts the mixing of polarizations from GR and enhances the net observed polarization



Expected Characteristics of Net X-ray Polarization

- Linear polarization sweep tells about the geometry (cf. “rotating vector model” in radio pulsars)

- The polarization signals can be very different even when pulse profile is similar

- Polarization will be perpendicular to **k-μ** plane even when field is non-dipole (for $B>10^{13}$G)

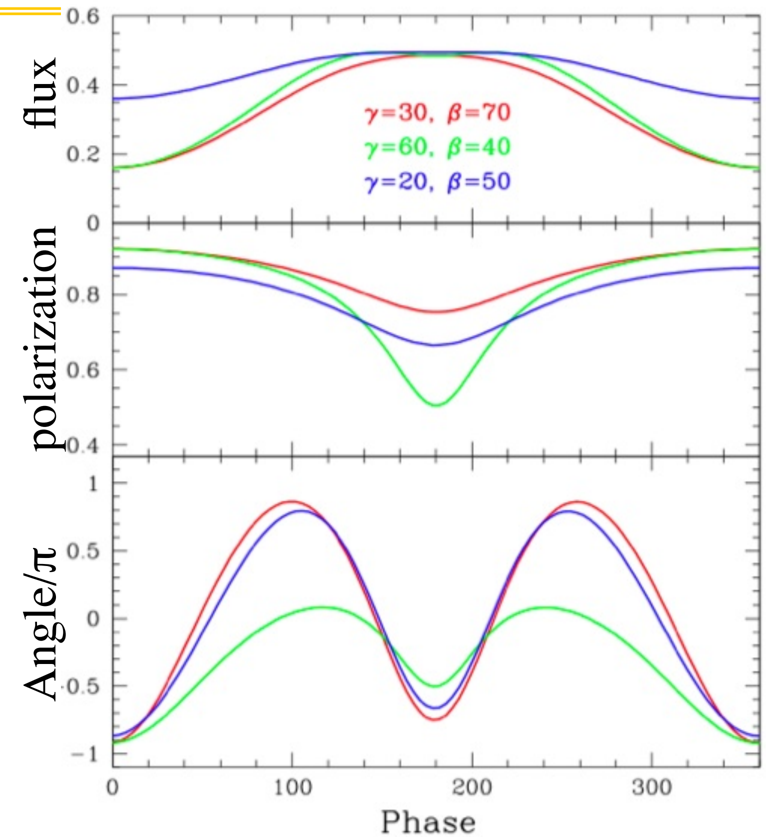
Polarization signals carry information about

•Geometry (magnetic field, rotation axis)

•Bound on field strength

•Weak dependence on M/R

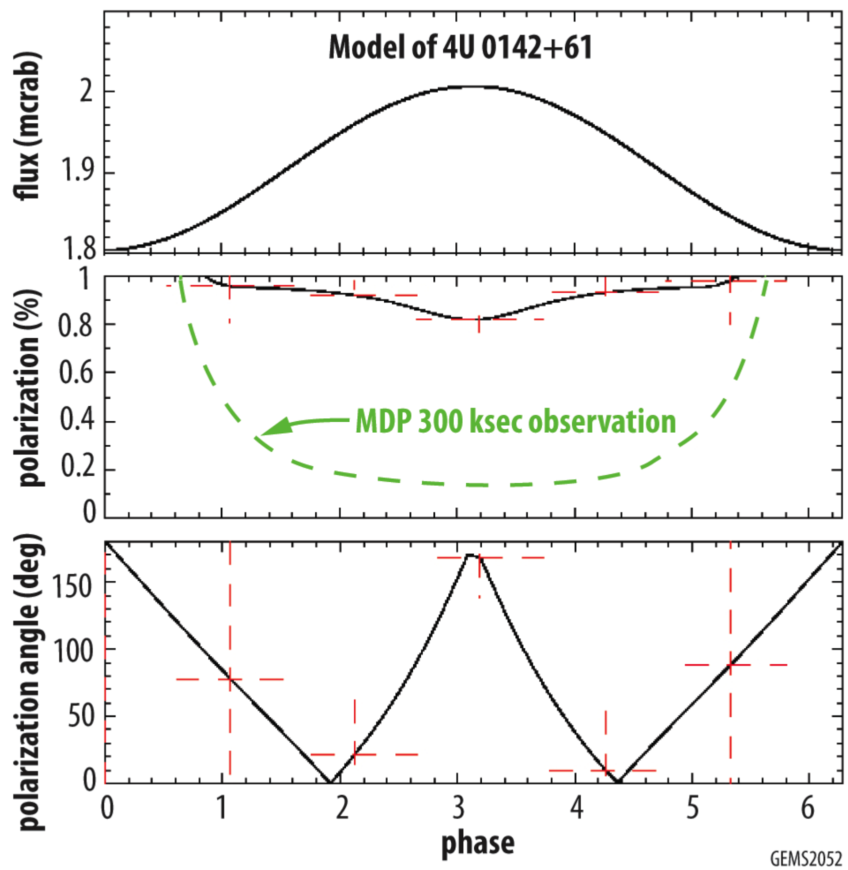
•Manifestation of QED effects



(Lai, Vanadelsberg, Heyl 2009)

GEMS will be able to measure the polarization from Magnetars

- With fields $B>10^{14}$G, strong intrinsic X-ray polarization is virtually certain
- Polarization will reveal field geometry and size and location of the emission region
- Observations during outbursts will measure changes in the field geometry
- This is thought to be the source of magnetar variability



Simulation of observation of the AXP type magnetar 4U 0142+61

(based on van Adelsberg &Lai 2006)

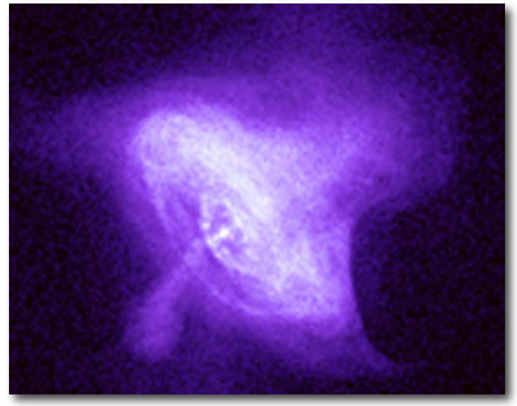
GEMS can test models for the geometry of the emission regions in rotation- powered pulsars

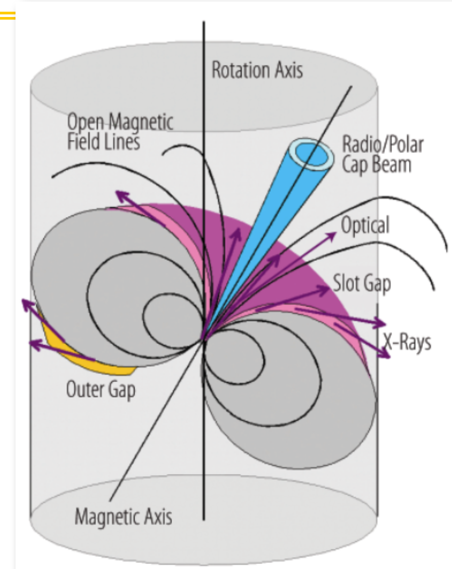
- Three models traditionally considered:

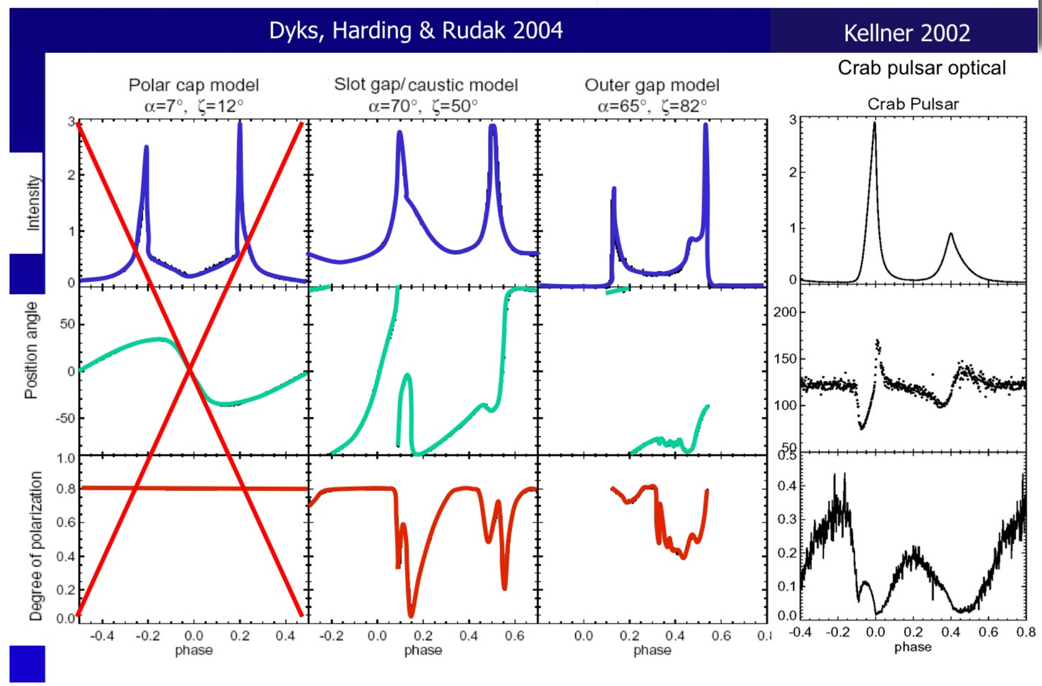
polar cap, outer gap, slot gap

- Distinctive signatures of likely models are due to caustics:
  - Large sweep in position angle (PA) through pulse peaks
  - Dips in polarization at peaks
- *Fermi* results clearly point to outer magnetosphere emission: outer gap or slot gap
- Polarization measurements
  - Constrain gap geometry
  - Help determine inclination and viewing angle

Chandra image of Crab

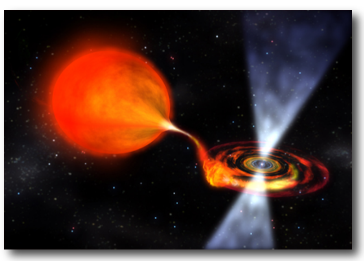




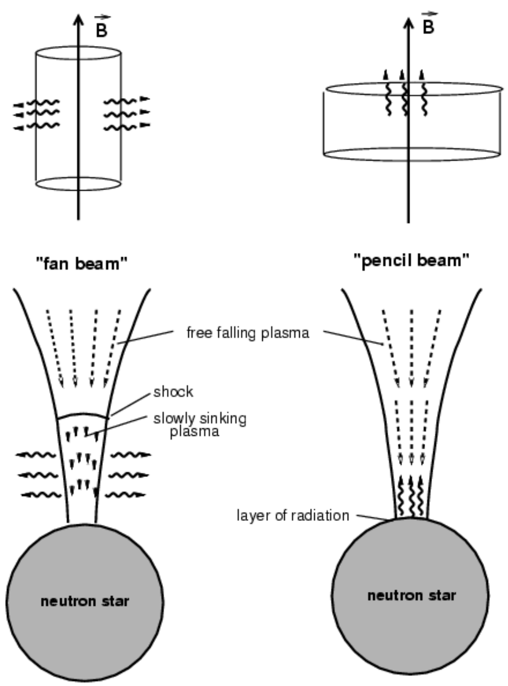


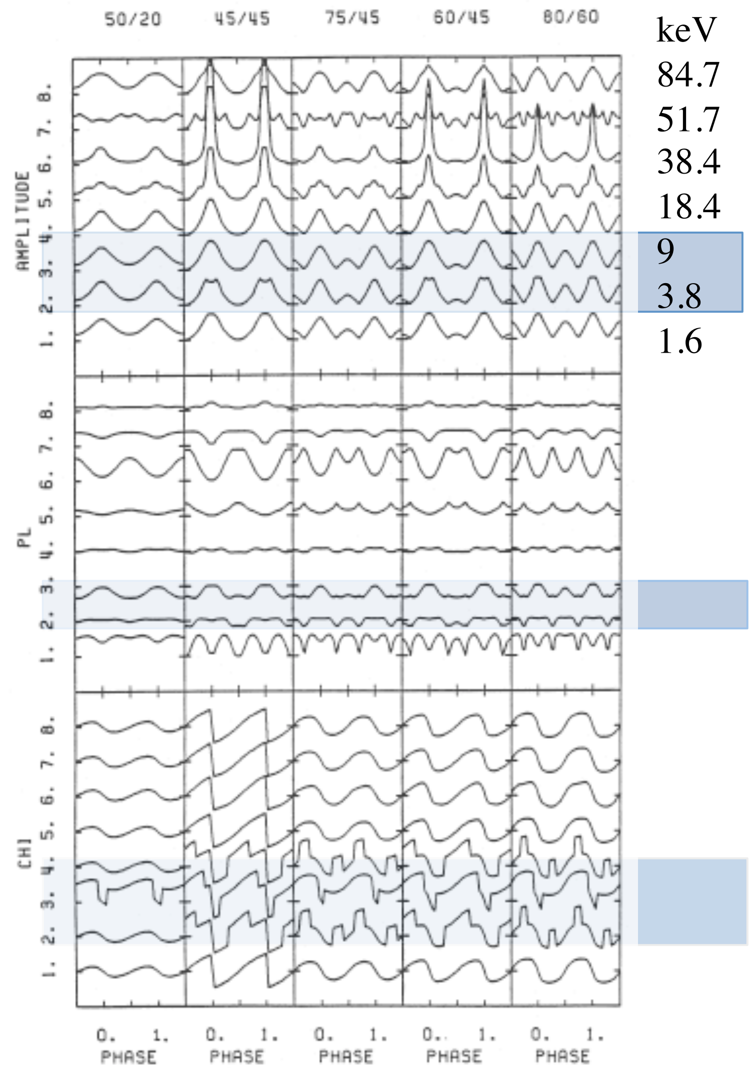
What is the Geometry of the Emission Regions in accreting Pulsars?

- In accreting pulsars,
  - are X-rays emitted in a pencil beam or fan beam?
- GEMS will observe very different polarization signatures depending on geometry



Artist's concept of binary accreting neutron star

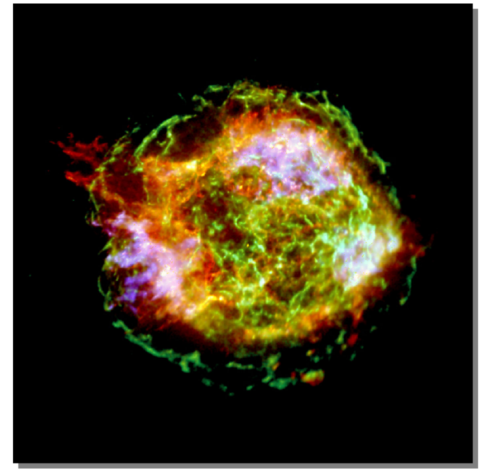




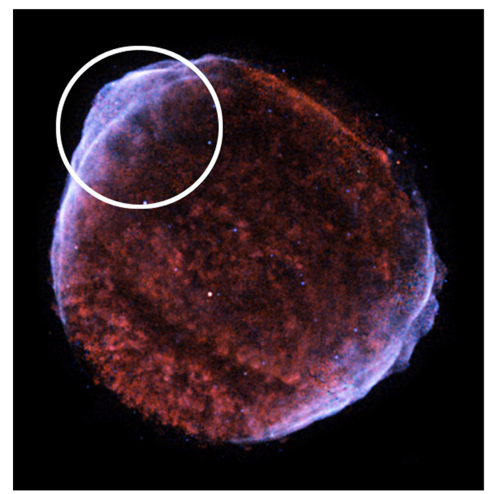
Pencil beam, from Mészáros et al. 1988
Relative phases opposite for fan beam

in Supernova Remnants, GEMS will probe Particle Acceleration

- X-ray imaging and spectral observations have shown:
  - Supernova remnant shocks are sources of synchrotron radiation from radio through X-rays
    - The shock thickness implies B fields are amplified
  - The shocks are sources of radiation up to TeV (10^{12} eV) energies
- Questions remain:
  - How are the B fields amplified?
  - Are the B fields tangled or coherent?
- The strength of the polarized X-ray flux will constrain these quantities



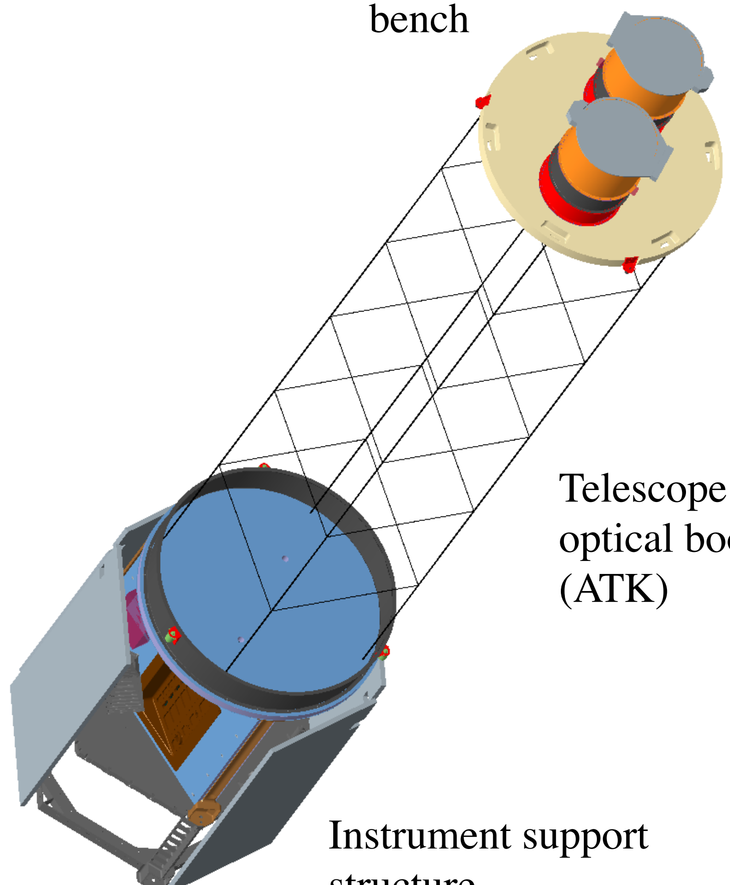
Cas A with Chandra



SN1006 with Chandra showing GEMS fov

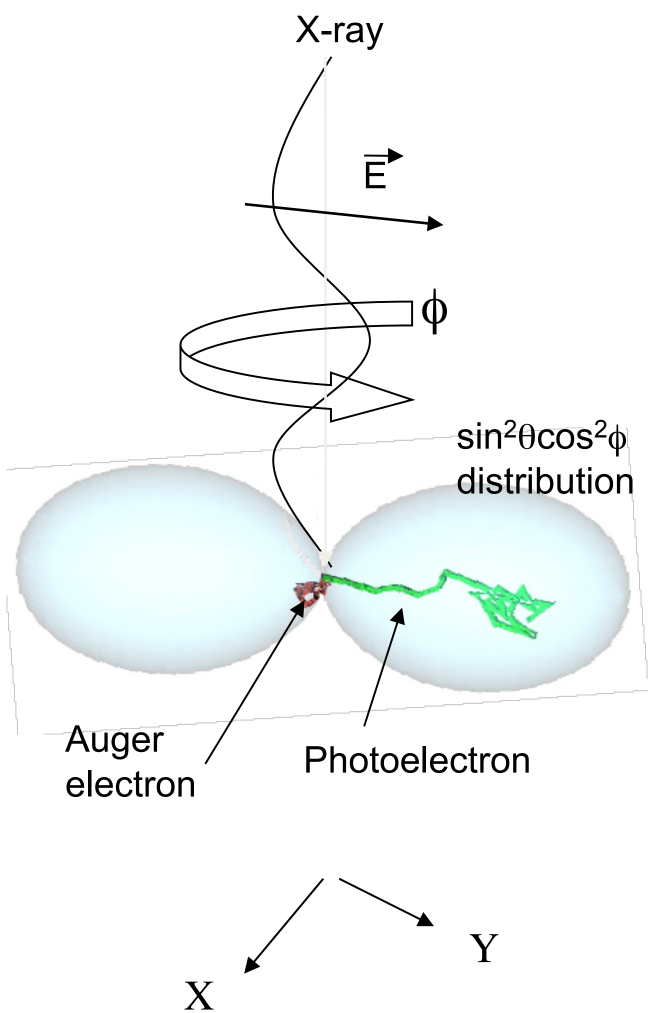
The X-Ray Polarimeter Instrument (XPI) -

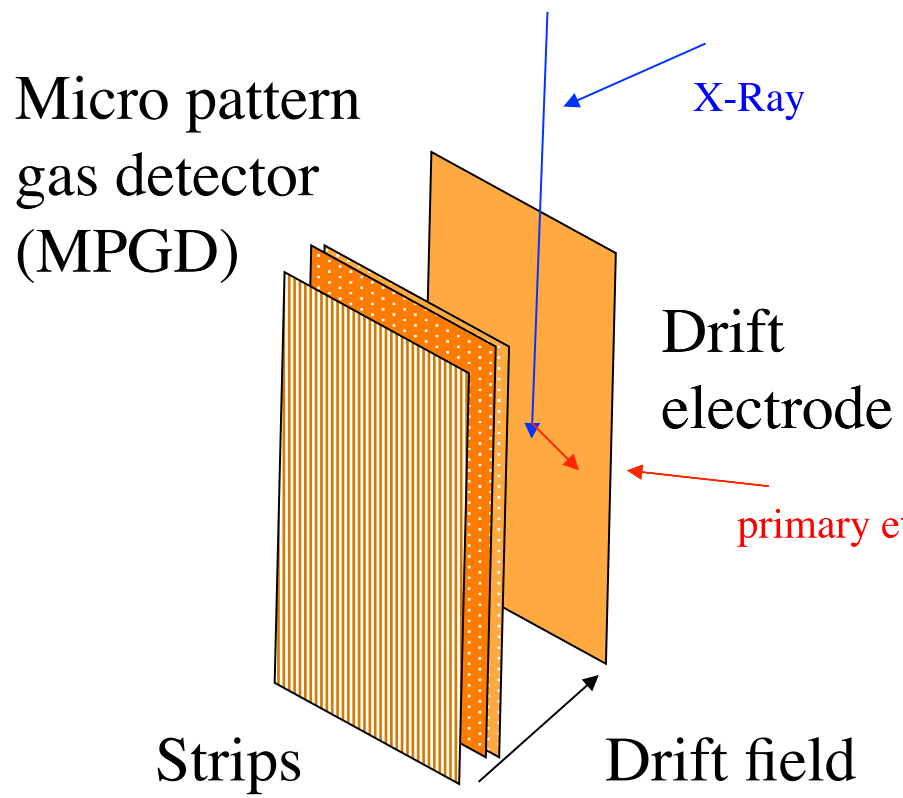
- 2-10 keV range
- 2 Mirrors with 4.5 m focal length (a Suzaku mirror, but 33 cm diameter versus 40 cm)
- Polarimeters imaging photoelectron tracks
- 2 independent telescopes (mirror and polarimeter pairs)



A Time Projection Chamber (TPC) is used to track the photoelectron paths

Measures the projection of the electron track in the X-Y plane with time and space measurements

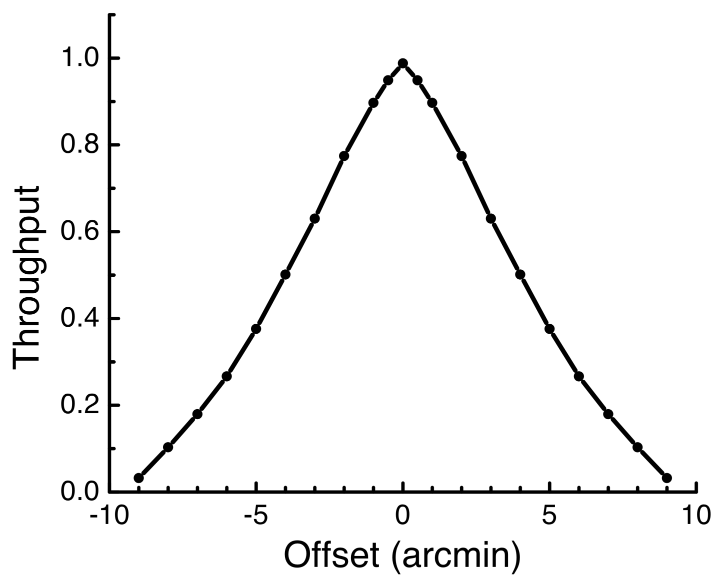




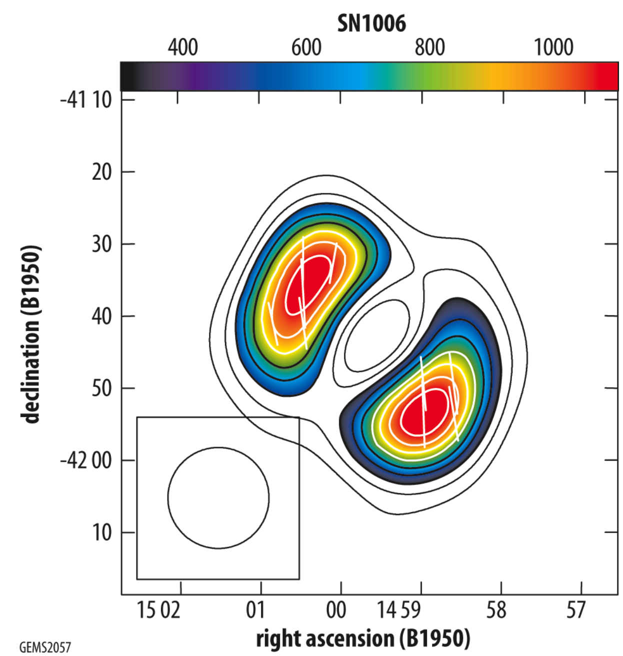
While the sky is not imaged, XPI has a useful field of view

Mirror and aperture geometry combine with the point spread function to give a field of view ~ 14 arc min

Convolution of telescope fov and ASCA image of SN1006 shows the contributions of the hemispheres



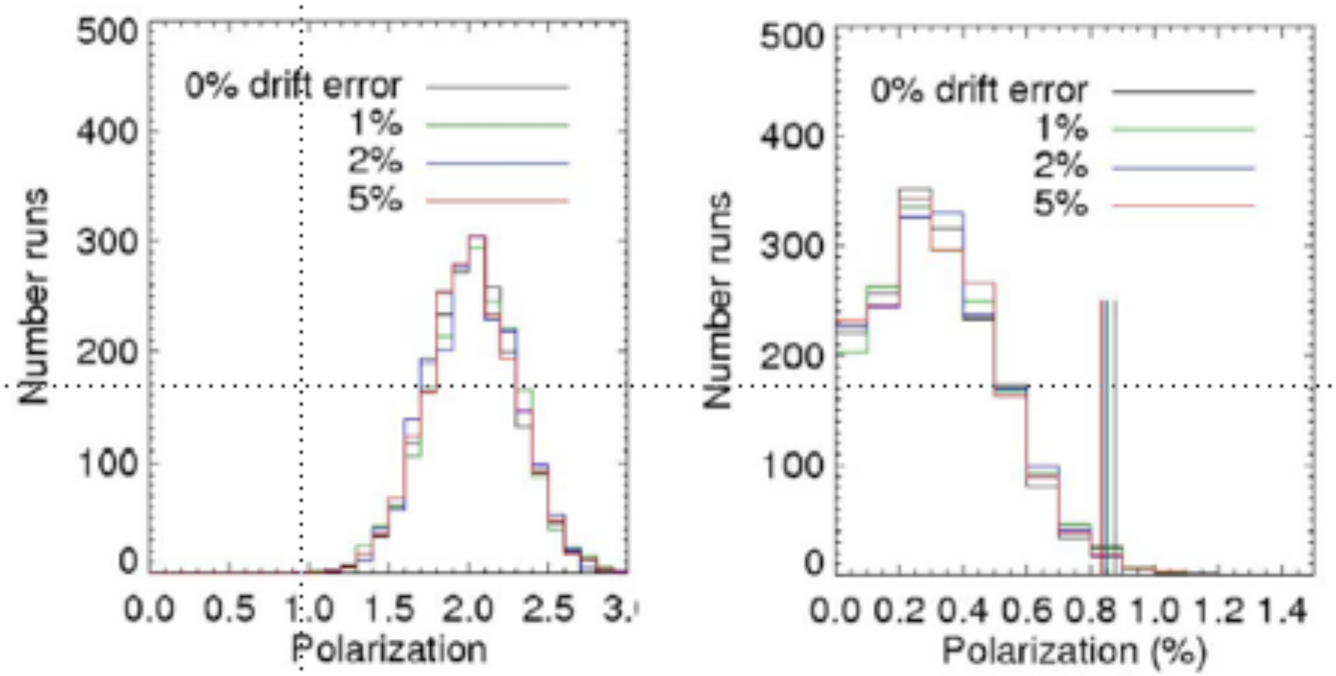
Response of current detailed design



The spacecraft and instrument will rotate together

The GEMS spacecraft, with the XPI will rotate at 0.1 rpm, about 10 times a spacecraft orbit, ~100 or more per observation

Simulations with introducing a detector-based false polarization when the data is mapped to the sky (averaging over the detector orientations): Distributions in measured polarizations are not significantly changed



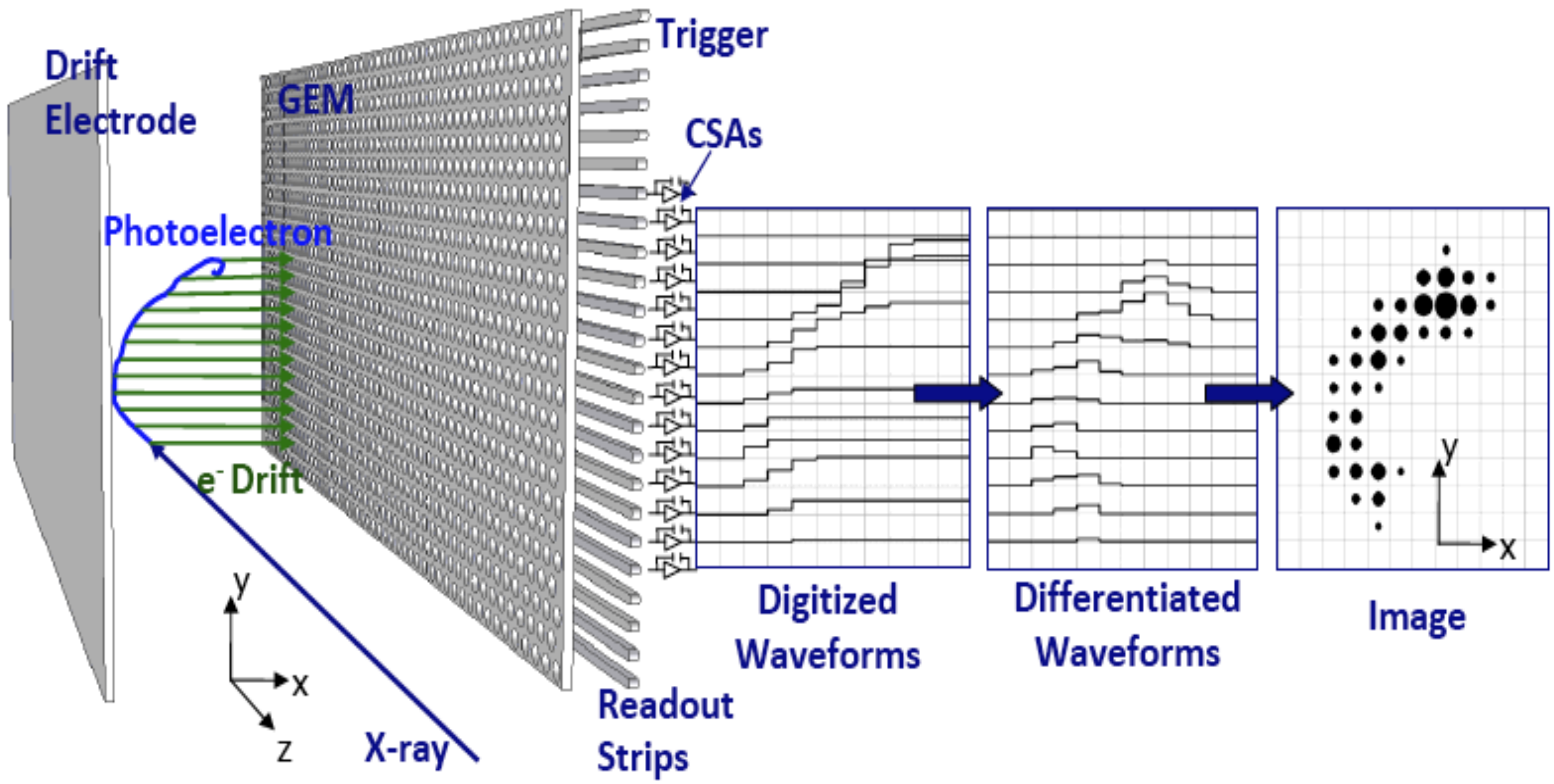
10^6 photons per trial, 2000 trials by Kaaret

The mission design

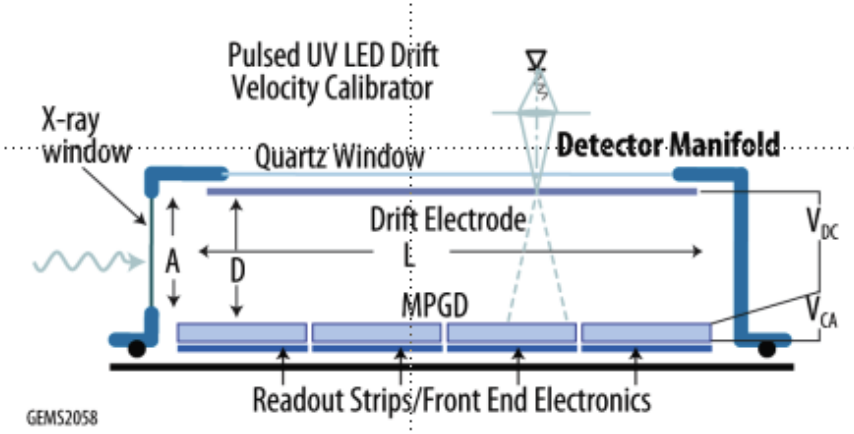
- Spacecraft bus from Orbital (proven heritage of AIM & GALEX)
- Low Earth Orbit at 575 km
- 28.5 degree inclination
- Pointing 90 ^{o} ± 25 ^{o} from the sun
- Long pointings (1 - 60 days)
- ~ 50 % duty cycle (considering earth occultations and South Atlantic anomaly passages with the voltage off)
- All the sky passes overhead in 6 months
- Mission Operations at Orbital's multisatellite facilities
- Downlink once per day
- Uplink once per week
- ~30 sources observable to important sensitivity limits in 9 months
- 10 month baseline mission duration with possible extension to enable 15 months of General Observer program

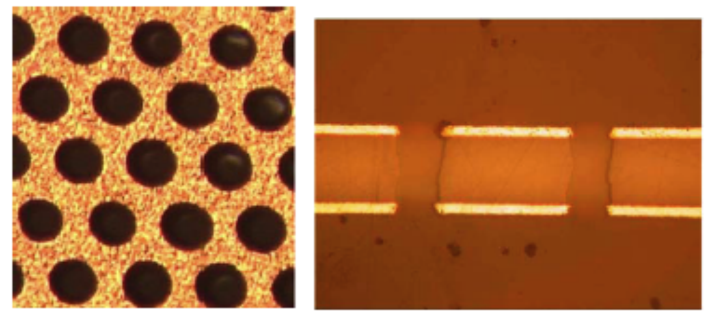
The TPC

- Image pixels are formed by readout strip pitch (y) and drift velocity/sampling rate (x)
- Quantum efficiency (depth) is perpendicular to readout (drift) direction



The components of the polarimeter have been tested and demonstrated





RIKEN-140T-LCP
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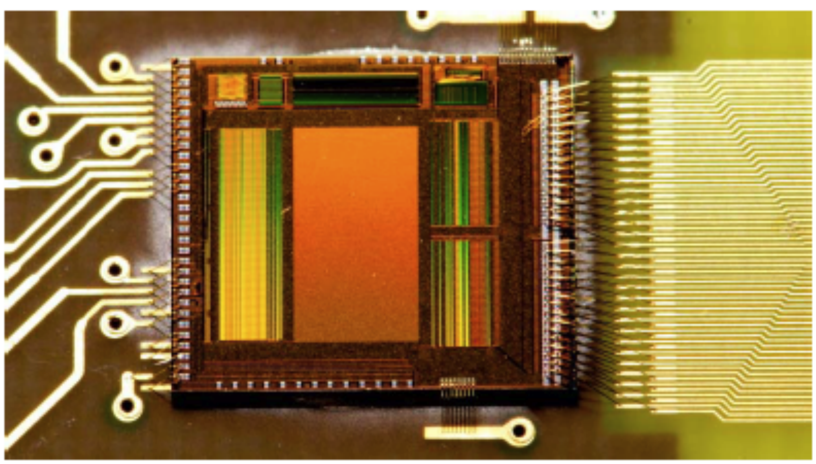
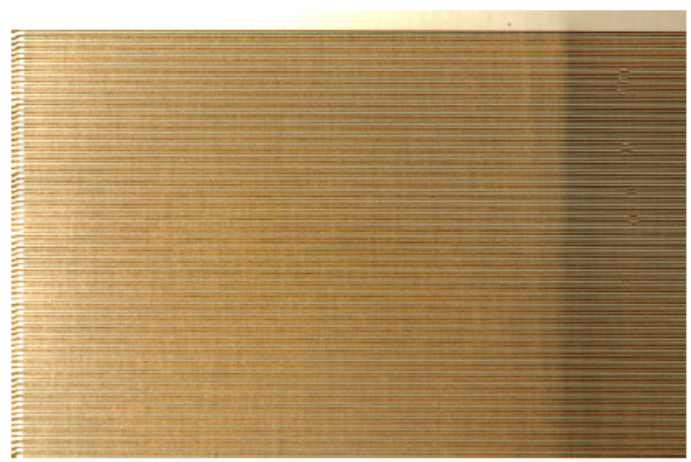
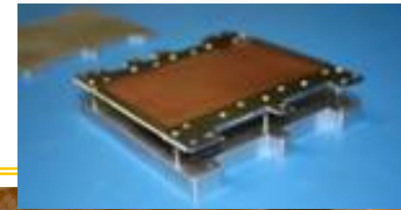


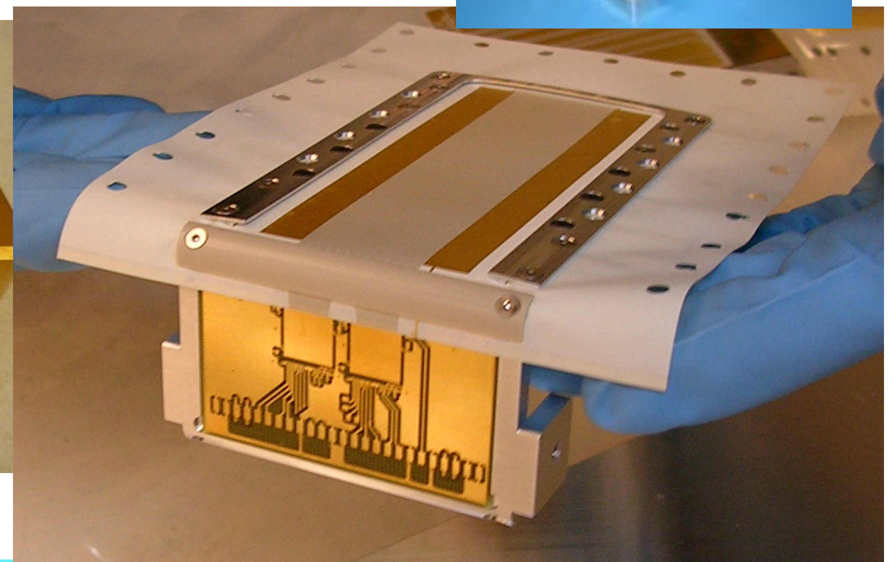
APV25 ASIC bonded to EDU strip readout

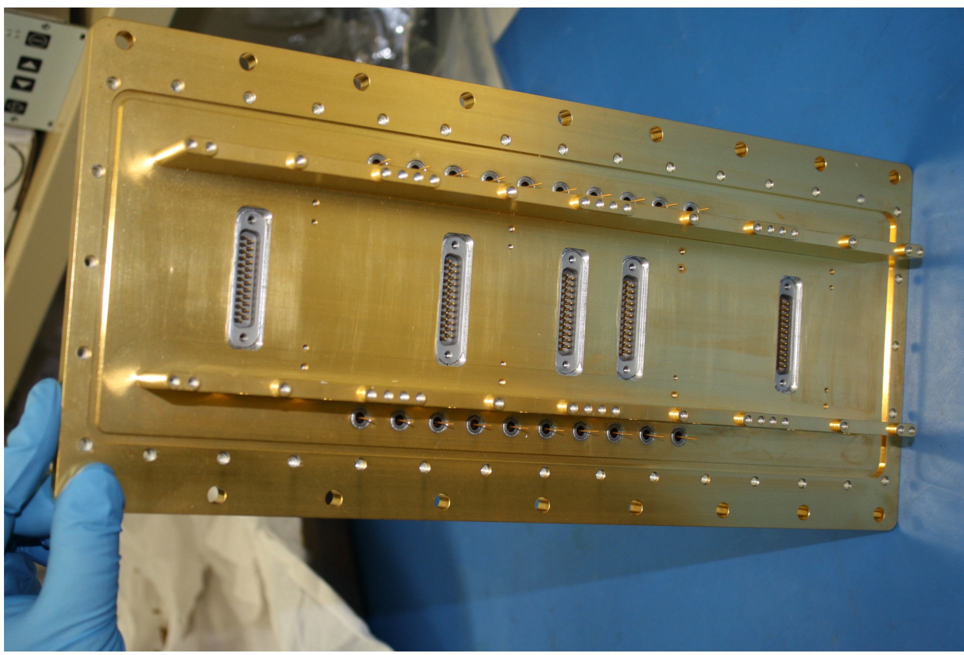


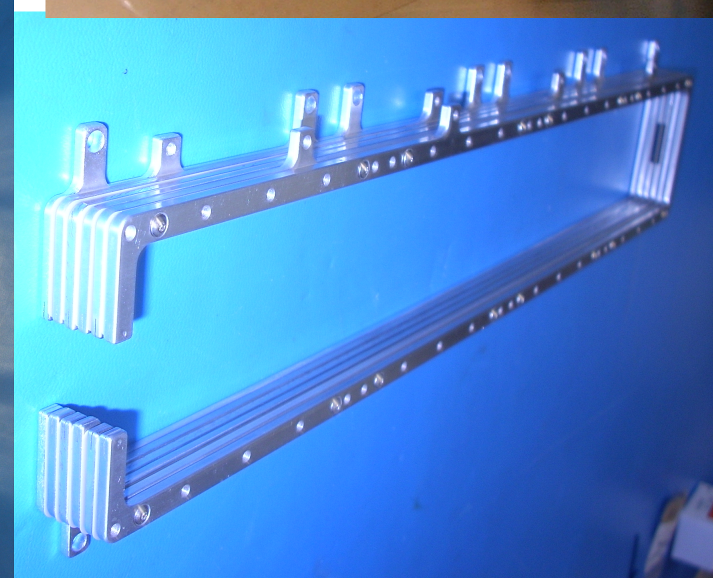
Readout strips on LCP, 121 μ pitch

ETU Hardware









GEMS sensitivity

- Minimum detectable polarization
  - 99% confidence

$$MDP = \frac{4.29}{\mu\sqrt{nRsT}}\sqrt{\frac{r+b}{r}} \approx \frac{4.29}{\mu\sqrt{C}}$$

μ= modulation for 100% polarized X-rays

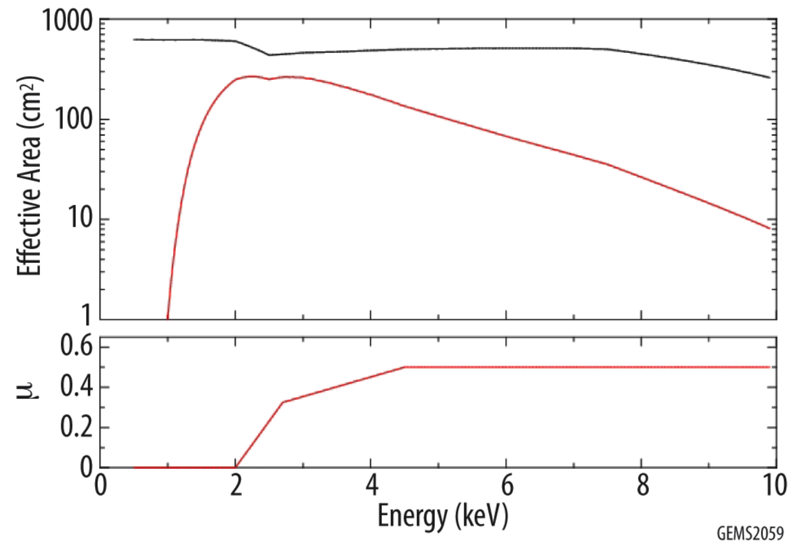
n = number of telescopes

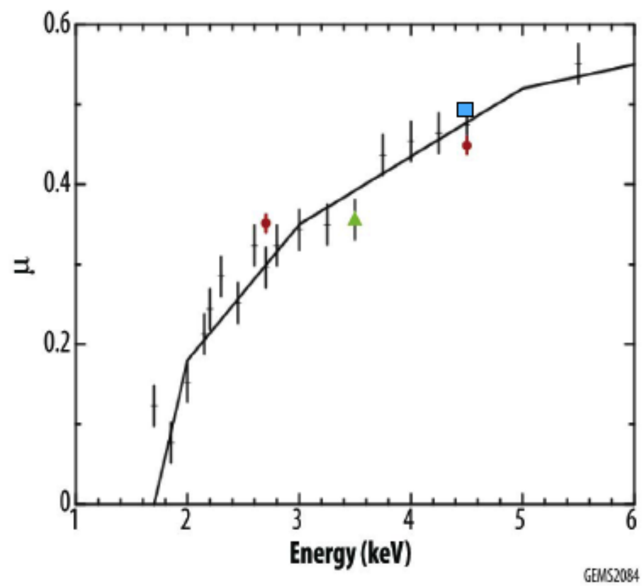
R = counts/s per Crab per 1 telescope

s = source strength in mCrab

T = observation time

(neglecting background < 0.2 mCrab)





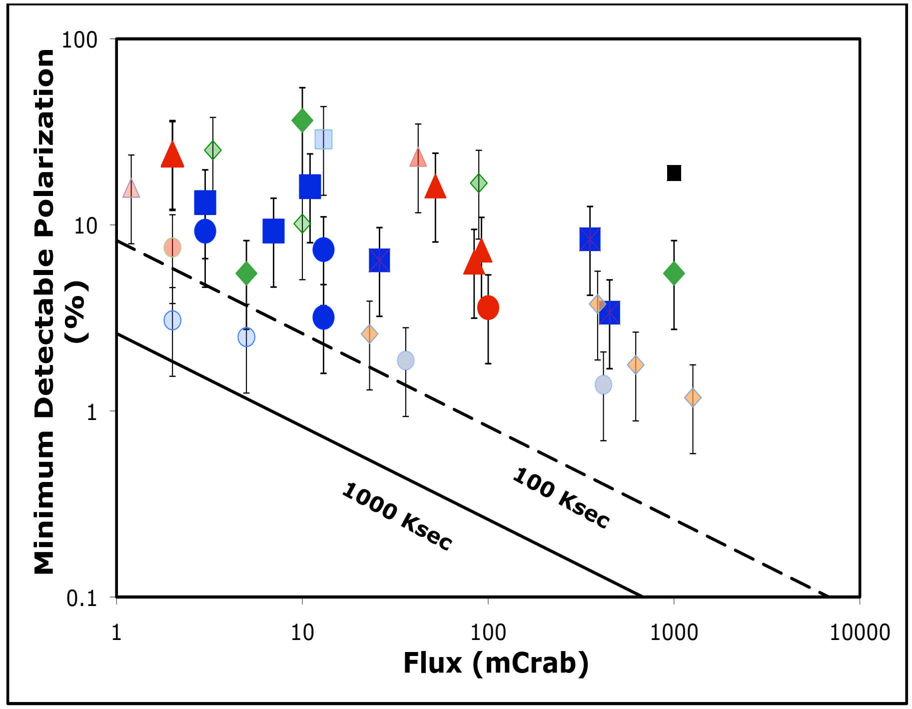
† Simulations with Penelope

+ Measured with discrete electronics

■Measured with APV25

GEMS observations

- The GEMS observing program:
  - 9 black holes
  - 5 pulsars and neutron stars
  - 3 supernova remnants
  - Plus comparable numbers of targets available for guest observers
- To address questions including:
  - Where is the energy released near black holes?
  - What is the origin of X-ray emission from pulsars?
  - What is the magnetic field structure in supernovae remnants?



■ Crab nebula observation

● ■ ▲ ◆ *Monte Carlo assignments* within a x 3 range of theoretical assignment

(smaller symbols denote possible guest observer targets)

The Gems Team

GSFC	PI: Jean Swank, Deputy PI: Keith Jahoda
	Chair Science Working Group: Tim Kallman
	Polarimeter scientists: Kevin Black, Phil Deines-Jones, Joe Hill
	Mirror scientists: Rob Petre, Peter Serlemitsos, Yang Soong
	Data: Tod Strohmayer, HEASARC archive: Lorella Angelini
	EPO: Jim Lochner
UI	Calibration and Student Experiment: Phil Kaaret, Zach Prieskorn
ARC	Analysis techniques: Jeff Scargle, Robin Morris
	Multiwavelength comparisons: Jesse Dotson
MIT	Simulations: Herman Marshall

GEMS Collaborators

Mathew Baring	Rice U	Magnetars, SNR
Alice Harding	GSFC	Pulsars, magnetars
Henric Krawczynski	Washington U, St. Louis	Blazars
Julian Krolik	JHU	Black Holes
Dong Lai	Cornell U	Magnetars
Craig Markwardt	UMD/CRESST	Science Operations
Jeff Martoff	Temple U	TPCs
Juri Poutanen	U Oulu	Black Holes
Steve Reynolds	NCSU	SNR
Rita Sambruna	GSFC	Blazars
Jeremy Schnittman	JHU	Black Holes
Toru Tamagawa	Riken	MPGDs

Conclusions - Astrophysics needs X-ray polarization and GEMS will open the frontier

- Theory provides abundant predictions of strong polarization in the 2-10 keV energy range from most classes of X-ray source
- These need confirmation/testing! X-ray polarimetry is essentially unexplored
- We can learn fundamental things: black hole spin, neutron star magnetic structure, supernova shock geometry.
- GEMS can accomplish these goals using a simple, robust design
- Gems will
  - launch in April 2014
  - carry out the proposed program in 2014 and
  - could carry out a general observer program 2015-2016